A SUMMARY OF INDUSTRY MDO APPLICATIONS AND NEEDS

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Abstract

The AIAA MDO Technical Committee has sponsored a series of 10 invited papers dealing with industry (and related) design processes, experiences, and needs. This paper presents a summary of these papers with emphasis on the needs of industry in the area of MDO. Together the 10 invited papers and this summary paper comprise an AIAA MDO Technical Committee "White Paper" on this subject. This summary paper contains; 1) a short synopsis of each paper and the industrial design it describes, 2) a sorting of all of the salient points of each of the papers into MDO categories plus a discussion of each category, and 3), a summary of industrial needs distilled from the papers. It is hoped that this summary paper will provide a technology "pull" to the MDO technology development community by presenting the industrial viewpoint on design and by reflecting industrial MDO priorities and needs.

1. Introduction

Upon the establishment of the Multidisciplinary Design Optimization Technical Committee (MDO/TC), a White Paper was prepared to assess the State of the Art in the MDO technical area[1]. Jointly written by founding members of the TC, the paper provided a brief history of aerospace design and made the case for integrating all the disciplines in the design process. The White Paper then reviewed recent developments, addressing in turn the human interface aspects of design, its computational aspects and its optimization aspects. The discussion continued with an approach to transitioning the design environment to Concurrent Engineering and a discussion of how MDO can support that transition. The White Paper finally concluded by stating that MDO provides a human-centered environment 1) for the design of complex systems, where conflicting technical and economic requirements must be rationally balanced, 2) that compresses the design cycle by enabling a concurrent engineering process where all the disciplines are considered early in the design process, while there remains much design freedom and key trades can be effected for an overall system optimum, 3) that is adaptive as various analysis/simulation capabilities can be inserted as the design progresses and the team of designers tailor their tool to the need of the moment, and 4) that contains a number of generic tools that permit the integration, of the various analysis capabilities, together with their sensitivity analyses and that supports a number of decision-making problem formulations.

Since the publication of the first White Paper, much work has been devoted to MDO as attested in the proceedings of the successive AIAA MA&O Symposia, for example. A number of detailed surveys have been written (see Sobieski and Haftka[2], for example), updating the research community to the latest developments in MDO in general, and in some subareas of MDO as well. The MDO/TC is taking the occasion of the current (7th) MA&O symposium to add to the constant dialogue between MDO users and MDO researchers. It invited designers from various organizations to contribute a technical paper describing a recent design exercise in which they have been involved and to take that opportunity to offer some insight into their application of formal MDO methodology to their problem. In particular, the users were asked to address whether they had used MDO, whether it helped or did not help, and what developments they needed to improve their process. This paper is a draft synopsis of the lessons gleaned from the various contributions. The paper will be reviewed and edited by the MDO/TC and it will be posted on the Web, together with the individual contributions, at the same site as the 1991 White Paper.

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It is hoped that this paper will provide some insight into what are the MDO developments most critical to MDO users (industry, or others). Because this paper is directly based on the inputs of only ten different design exercises, it cannot be presented as a consensus opinion on what MDO should be for the engineering design process however it is felt that a very good representation and cross-section of industrial applications, challenges and needs are given and that the conclusions of the data contained here will be helpful to the MDO technology development community for prioritizing future MDO development.

For the purpose of this paper, we use the following definition for MDO: *A methodology for the design of complex engineering systems and subsystems that coherently exploits the synergism of mutually interacting phenomena.* One can argue that ever since systems have been designed, multiple conflicting requirements have had to be taken into account and therefore multidisciplinary process have always been used. This point is not debated here, however the key word in the definition is methodology. *MDO* provides a collection of tools and methods that permit the trade-off between different disciplines involved in the design process. *MDO is not design but enables it.*

Ideally the MDO-based environment of the future will be centered on the IPD design team. To facilitate its use the MDO process will be interactive and will permit the design team to formulate its design problem in real time as the design issues become clear. Specifically, the MDO process should be flexible enough so that the problem formulation, applied constraints, and the level of simulation can all be specified by the design team. To facilitate technical communication, the design team may wish to create and update a single parametric model of the system being designed and reshaped it (automatically) in the course of the design. It could be used to automatically generate consistent computational models for simultaneous use in various disciplines. An environment that offers visibility to the process, permitting the team to monitor progress or track changes in the problems dependent or independent variables will be beneficial. All along, the process control would remain squarely in the hands of the design team. The environment could be distributed to reflect the nature of today's design projects. Specifically design exercises can be distributed over many different groups, many sites, often even in different countries. In addition to providing a challenge to the management of the process, its distribution also may provide additional resources as it could open up a network of computing nodes that could be harnessed to carry out the process. The ideal environment would automatically route the computational process to the most suitable/available resources. Since very large amounts of data will be generated, they could be stored in a distributed fashion as well for convenience and efficiency, but the environment would make the data readily available to all design team members in a transparent fashion.

The paper is written from the perspective of the user of MDO, and begins with a brief summary of the papers contributed to the sessions by the designer teams. Then, the challenges and issues addressed by the different papers are identified and categorized, forming a taxonomy of MDO, as perceived by the designers. The paper concludes with an assessment of industry needs and some recommendations for MDO development. Note that Sobieski made an earlier attempt at developing a taxonomy for MDO[3] ; his efforts could be seen as a 'Technology Push' approach at defining the needs from MDO, being developed from an distinguished experience in government research. The new taxonomy offered in this paper is coming largely from the other 'Application Pull' perspective. It is expected that the combination of both perspectives will prove thought provoking and helpful to the planning and development of MDO technology.

2. MDO Applications, A Synopsis

A short synopsis of each paper is presented in this section. The basic design problem encountered in each paper is summarized along with highlights of a few of the main points made. Figure 2-1 gives a general overview of where each paper lies with reference to fidelity level and "MDO level." MDO level is loosely defined as follows. Trade studies indicate that point designs were generated and graded relative to each other without formal optimization. "Limited Optimizations/Iterations" indicates a disciplinary sub-optimization or one with limited disciplinary interaction. Full MDO indicates vehicle level optimization with most critical disciplines involved.

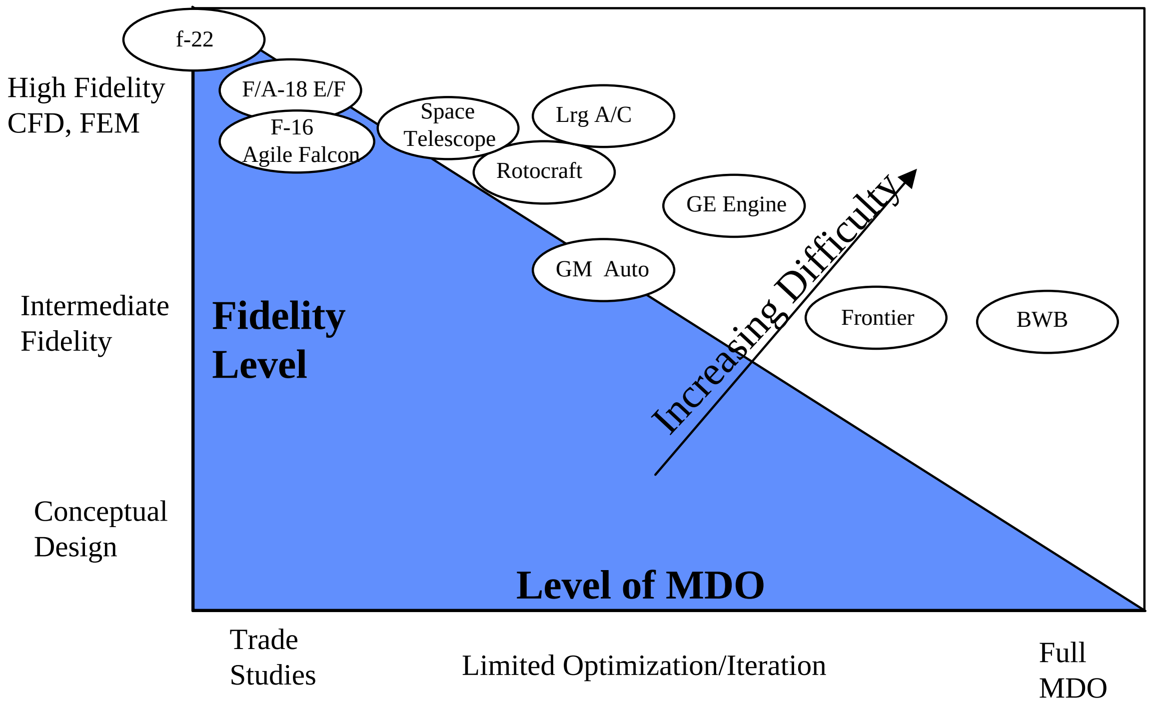

Figure 2-1: Distribution of Design Process Fidelity and Level of MDO

The Challenge and Promise of Blended Wing Body Optimization

Wakayama and Kroo[4] describe the application of the WingMOD MDO process to the minimization of the BWB Take-Off-Gross-Weight. The process is fully multidisciplinary and includes design variables for planform shape/size, mission, aerodynamic, structural sizing/topology, fuel/payload, and trim schedule (134 in all). WingMOD uses a close-coupled approach using intermediate fidelity disciplinary analyses for high aspect ratio wing aircraft. An optimization framework (Genie) makes calls to all of the analysis routines, using finite differences to compute sensitivities. The aerodynamic analyses include the vortex lattice method and quasi two-dimensional compressibility corrections. The structural sizing and constraints are based on aeroelastic loads and deflection analysis, simplified buckling, and stress analysis of simple beams. The weight is based on the structural analysis corrected by some statistical data. A wide breadth of practical constraints are considered (705 in all) along with 20 design flight conditions that cover most of the critical design considerations.

One of the main points of the paper is that all critical constraints and disciplines (breadth) must be included to produce a realistic/practical configuration and that all critical physical mechanisms should be included, to some level of fidelity (depth), to reach the highest potential benefit of integrated design. The main need of the process is inclusion of CFD (mainly for propulsion/airframe integration) into the process without rendering it intractable. Indeed, this close-coupled system makes many (thousands) of calls to the analysis routines.

Issues in Industrial Multidisciplinary Optimization

Bennett *et al*[5]describes the application of the GM IVDA (Integrated Vehicle Design Analysis) system to the maximization of automobile fuel efficiency. The system is composed of both commercial (ODYSSEY, NASTRAN, LPM, DYNA3D, CAL3D, ADAMS,) and GM codes (aerodynamics, solar load, fuel economy, and others). The user can configure the process within IVDA to produce an optimization sequence which was done for several examples in an *ad hoc* manner. The examples described included one global design variable (vehicle length), and suboptimizations are performed in the local disciplines (structural member cross-section design). The local designs and analyses feed a results database which is then fit with approximations. For instance the aerodynamic drag data was a neural net fit to test data. The optimizer then uses these approximations to re-design the vehicle.

The authors make the point that, in an industrial design environment, the design process does not necessarily fit a particular MD algorithm, rather, the implementation needs to be reconfigurable, on the fly. This introduces the idea of a toolbox of MD tools and off-the-shelf specialized tools that can be interfaced automatically, with the provision that "*... a menu of appropriate actions should be generated to guide the user through the process.*"

Boeing Rotorcraft Experience with Rotor Design and Optimization

Tarzanin and Young[6] describe an exercise of optimization to reduce helicopter blade hub dynamic forces. The objective function is a weighted sum of hub forces and moments. The optimization process is tightly coupled and uses an analysis simulation system maintained by several disciplines. Two levels of fidelity are available in this simulation; an approximate analysis level that requires 1 minute per function call, and a high fidelity level that requires 30 minutes per call. The authors make the point that the complexity of the detailed analysis led them to fully integrate their high fidelity codes, thereby obviating the need for any decomposition method. Optimization can proceed by interfacing a single optimizer with the integrated high-fidelity analysis. Practical verification of the benefits of this MDO approach was obtained with wind tunnel tests.

The design space encountered in this class of problems is characterized by many local minima and the paper describes several techniques for arriving at the global optimum and overcoming non convergence. Some of these techniques involve probing unexplored portions of the design space by: 1) employing multiple starting points, 2) initially employing loose constraints and gradually tightening them down to the required value, 3) allowing the constants in the objective function to take large excursions and then adjust back to the proper value, 4) updating aeroelastic loads at various times during the optimization.

The F-22 Structural/Aeroelastic Design Process with MDO Elements

Radovcich and Layton[7] describe a process for the detailed structural design of the F-22 aircraft after the configuration has been fixed. The focus of the effort is the minimization of weight while satisfying all of the detailed stress safety margins, flutter margins, and fatigue life requirements. This involves modifying active controls to alleviate loads and includes filtering control laws to eliminate unfavorable interactions resulting in flutter. Design considerations include, detailed part geometry, materials, external loads, elastic-to-rigid ratios, stiffness, mass, and flight control laws.

A single high-fidelity air vehicle FEM is a key requirement for the success of this effort. This FEM is used for stress, loads, flutter, allowables, internal loads, and checking of aeroservoelastic affects. This FEM is the main feature in a tri-company coordination effort, and it payed for itself many times over in providing a straightforward process and in facilitating communication. The only restriction on the FEM is that it not overload the Convex 10 terabyte storage capacity. The design process consists of cycling all of the necessary analyses and design steps. Some of the disciplines are iterated several times within the global cycle. In addition, because of differences in discipline cycle time, several disciplines are at different stages, being 1, 2 or even 3 cycles behind the current global cycle. In the time allotted, four global cycles are carried out, however, the inconsistencies between the discipline stages do not seem to affect convergence greatly.

The Role of MDO within Aerospace Design and Progress Towards an MDO Capability Through European Collaboration

Bartholomew[8] presents three European MDO projects; 1) the GARTEUR regional transport aircraft structural optimization, 2) the EU IMT project where the A3XX transport aircraft direct operating cost (approximation) is minimized and, 3) the ESPRIT Frontier project where a Pareto front is identified for a multiple objective problem, and where trade-offs between the different objectives are identified.

In addition to the examples, a discussion of MDO in general and Europe in particular is presented. The MDO process of choice is loosely coupled, and multilevel. At the lower level, it uses a detailed design process normally used by engineers. An integrated software system is needed that has a flexible user interface, provides for checking all along the way, and uses standardized product data formats (STEP).

MDO Technology Needs in Aeroelastic Structural Design

Hoenlinger *et al*[9] present explicit answers to the questions posed by the organizers of this session. The highlights of their paper are two tables, and accompanying discussions, that provide a wealth of information on past experience with structural sizing/optimization and expert opinions on what is needed in MDO. The industrial applications range in time from 1985 to the present and cover the ACA, X-31, Ranger 2000, Stealth Demonstrator, and the "MDO Aircraft" (A3XX). The history of the development of the LAGRANGE aeroelastic structural optimization software is sketched, ending with the decision not to extend this system to the controls discipline as it is thought that a more general architecture is warranted and that it is better to include LAGRANGE itself in a more general architecture (e.g., iSIGHT). The existence and application of a rapid parametric FEM model generator for high aspect ratio wings is also discussed.

Like several other contributors, the authors points at the fact that there are serious organizational aspects in introducing MDO in an industrial environment. ("..*no coordinating position for MDO is present in typical industrial hierarchies.*")

A Collaborative Optimization Environment for Turbine Engine Development

Rohl *et al*[10] describe the development of an MDO process for the design a jet engine rotor disc; they show that a significant part of the challenge to performing MDO is to be able to do MDA (Multidisciplinary Design Analysis). The first order of business is feasibility (fatigue life and distortion tolerance). The second consideration is minimum weight, both for the finished part and for the billet (cost). The components of the process are: mechanical design, thermal cycling/loads, forging optimization, heat treatment optimization, machining simulation and life prediction. The mechanical design to meet the mission requires material properties, residual stress, and life prediction which are not known ahead of time and are determined in the forging, heat treatment, and machining simulations and suboptimizations, and the life prediction analysis. Forging is a minimum billet weight optimization (using DEFORM) with constraints on the forging requirements. Heat treatment has conflicting objectives for its suboptimization; i.e. maximum material properties, with minimum residual stresses and requires very high fidelity meshes. The authors point to the fact that the complex analysis capability resulting from the integration of the individual simulations required is not as smooth as desired, and that large step size finite differences are required to obtain robust derivatives.

The MDO process was initially implemented in iSIGHT and both the CSSO and CO decompositions, were tried. These proved impractical due to the nature of the problem and the requirement for high fidelity. A modified sequential process is suggested but this work is still in progress. Currently most of the emphasis is on the disciplinary tools and automation of these high-fidelity simulations. Specifically, two "tool kits," the Product Modeling Kit (PMTK), and the Discrete Analysis Modeling Kit (DMTK) are being developed under DARPA contract.

Multidiscipline Design as Applied to Space

Lillie *et al*[11] describes a systems engineering process for the feasible and affordable design of the NGST (Next Generation Space Telescope). The final product is a baseline design and the associated technology development necessary to implement the design. Five IPD Teams are used to design the telescope; 1) Optical Telescope Assembly (telescope structure), 2) Science Module (instruments), 3) Spacecraft Systems (power, propulsion, vibration and thermal control), 4) Operations Systems (ground systems, data handling, operations), and 5) Systems Engineering (Integration of systems and requirements). Requirements related to targets, observations, aperture, quality, imaging spectral bands, stare time, agility, pointing stability, imaging field of view, coverage, field of regard, lifetime, and cost make this a very challenging design for feasibility. The process is one of multidisciplinary integration. An example is the requirement for minimum contamination of the telescope optics from the propulsion system.

The design is presented as a series of mostly discrete decisions, few of the variables used are continuous. Usually a short list of available options exists for each choice. The importance of each of the requirements is classified as; 1) required, or 2) highly desired, or 3) desired, and 4) goal. The design decision is made based on the ability of the option to meet the requirement, the importance of the requirement, and the performance impact of the choice. Currently this TRW team is assembling a full structural, thermal, optical multidisciplinary simulation (not reported in the paper). Their objective is to "optimize" the design using the simulation. The issues with the simulation involve interfacing various systems together, converting and transmitting data among the three disciplines and developing a common model.

Multidisciplinary Design Practices from the F-16 Agile Falcon

Love[12] describes the process for determining the "best" design for a more "agile" F-16 aircraft at reasonable incremental cost. "Best" is not formally defined but involves ranking of discrete designs on the basis of maneuverability, controllability, weight, and producibility. The design is carried out in two steps, and the wing planform shape is selected in the first step, its twist and camber distributions in the second. A baseline was available for the new "agile" design and variations are developed about this baseline. Specifically, wing span, sweep, and area variations are analyzed and tested using 6 discrete design points. No one configuration provided superior performance. A new baseline was derived from the aerodynamic, weight, and system interface studies performed using a qualitative process. Further design refinements/studies are performed about the new baseline which consider variations in basic camber and twist distributions of the wing to enhance agility. Aeroelastic tailoring is used to optimize the new baseline, as well as a wash-in and a wash-out wings (i.e., wings that twist up or down, with increased aerodynamic loads). A ranking table that considered maneuverability, controllability, weight, and producibility was used to select the best of the three cases.

The author makes the point that "... the approach to achieve integration would probably be the same today (1998) as in 1988-89. The differences in the overall process would be in the tool selection... and the amount of data generated."

A Description of the F/A-18 E/F Design and Design Process

Young *et al*[13] describe the re-design process of the F-18 to meet multiple missions not originally intended for the original aircraft. Some of the increased requirements involved: carrier suitability (landing weight), strike mission (payload), fighter mission (range), increased survivability, maneuverability, growth potential, and others. The objective is to reach a feasible design at acceptable cost and a "Stop-Light" (red, yellow, green) process was used to grade each requirement. Seven discrete configurations are analyzed and graded by an IPD Team. Only two configurations had no red stop signs. Of these two, one had slightly better grading and lower cost than the other and this one is selected. Some of the design changes include: a 25% wing area increase, a snag in the leading edge, an enlarged leading edge extension (LEX), a thickness-to-chord ratio increase, enlarged inlets, and an added third weapons carrying station. The authors put a lot of emphasis on the building of an aerodynamic database made of a combination of CFD results and wind tunnel data which will prove critical to good aeroelastic optimization.

This paper also describes the IPD Team function and process, the Cost/Schedule Control System (C/SCS) accounting system, a Technical Performance Measurements (TPM) tracking system, and finally a section answering questions on, barriers to MDO and future needs.

3. Industrial Challenges and Issues

Selection of Categories

Many of the issues, needs, conclusions and salient points gleaned from the 10 papers are summarized, categorized and discussed here. The categories used here were inspired by a classification of "MDO Conceptual Elements" (MDO Taxonomy) given by Sobieski[3] but modified to reflect industrial needs, prospectives, and priorities. One such modification is the addition of a general classification dealing with "Management and Cultural Implementation" issues in the industrial environment. The industrial influence on Sobieski's Taxonomy was derived, in part, by a series of hypothetical questions (Figure 3-1) that an industrial designer might ask before designing an MDO system to solve his particular problem. These questions range from "What is my design objective?" to "How do I make it happen at my plant?"

Questions Asked by an Industrial Designer

1) What are my design objectives and critical constraints
2) What are my disciplinary analysis capabilities/limitations/Automation level
3) How do I get critical high fidelity elements into my design in an efficient manner?
4) What design process steps are needed to meet my design objective most efficiently and to know that I have reached my objectives and satisfied my constraints?
5) What MDO or design formulation do I need or what formulations are available to me?
6) What kind of approximation analyses are required?
7) How do I overcome Optimization problems (scaling, smoothness, robustness, effic.)?
8) How do I feed data among disciplinary analyses and the MDO process?
9) How do I overcome computing and data handling issues
10) What is the easiest way to visualize my design space?
11) How robust is my design and how do I check it?
12) Are there commercial systems that can effectively help me?
13) How do I make it all happen at my plant?

Figure 3-1: Concerns of an Industrial Designer Prior to Setting Up an MDO Process

The final categories or MDO elements selected for this paper are shown in Figure 3-2. There are four general categories which include design formulation issues (prompted by questions 1, 4, 5, and 7 in Figure 3-1), analysis capabilities (related to questions 2, 3, 6, and 11), information management (see questions 8, 9, 10, and 12) and management and culture constraints (question 13). Each general category contains several sub-categories of its own.

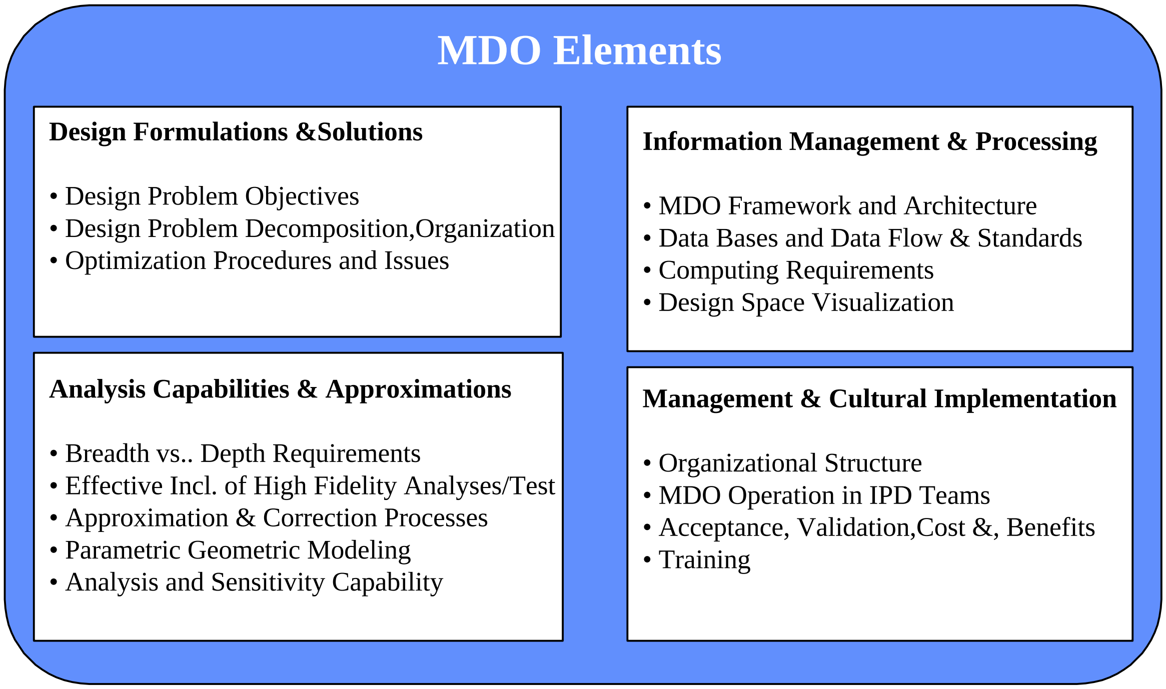

Figure 3-2: MDO Elements Grouped by Categories (MDO Taxonomy)

Each of the salient points from the 10 papers have been summarized into short one-line sentences. An initial is placed at the end of each of these sentences to identify the author from which they came. These points (one-liners) were sorted and placed in the categories given in Figure 3-2. The results of this sorting is given in Appendix I. A legend at the beginning of the Appendix gives the key relating the initials to the paper authors.

Discussion of Categories

A general discussion of the challenges and issues associated with each of the categories (shown in Figure 3-2) is presented here. The basis of these discussions are the sorted one-line salient points presented in Appendix I. The content of the discussion is mostly taken mostly from the pertinent items listed in each category, however additional interpretations, generalizations and the experience of the current author are also sometimes included.

<u>*Design Problem Objectives*</u>

The range of industrial design objectives sampled in the 10 papers is illustrated in Figure 3-3. The scale is an imaginary continuum of problem statements that ranges from making a design satisfy all requirements (i.e., feasible), to finding the optimum design for several objective functions. Intermediate possibilities are improving a feasible design and finding a single-objective optimum. Most of the papers included in this series are lumped in the "Feasible" and "Optimal" categories. However, even though many of the design problems are cast as optimization problems it is probably true that the real goal of the effort is an improved design. For example, in the helicopter rotor design problem discussed by Tarzanin *et al* [6], the optimized design was tested to see if it presented an improvement over earlier designs, not to see if the improvement matched the predicted optimum. Young, Anderson, and Yurkovitch[13] show that another implicit goal of the effort is probably design robustness since point designs can be sensitive to unknown problem parameters and are not always of practical value. Bartholomew[8] discusses a pareto-optimization approach; a parameterized series of optimizations carried out to effect trade-offs between different conflicting objectives.

The authors describe a situation where, generally, the problem statement is not known a priori. Rather, it is defined in an interactive fashion in the course of the design exercise. As an initial statement is adopted, a particular design emerges that may be lacking in one way or another. At that point, the problem statement is modified to address the shortcomings of the initial design. This process is continued, until a satisfactory design is obtained.

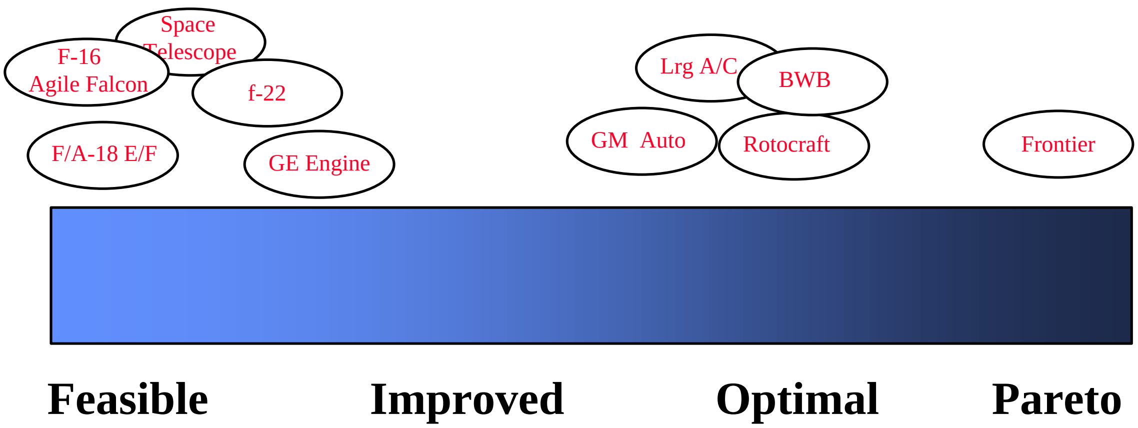

Figure 3-3: Range of Design Objectives

Design Problem Decomposition and Organization

The consensus appears to be that loosely coupled systems that can work with legacy analysis codes hold the most potential for future advances (see, for example Bennett *et al*[5], Bartholomew[8], Hoenlinger *et al*[9]). Such a system also affords flexibility and can be reconfigured as the problem formulation evolves, as indicated in the previous section. This implies a need for an off- the-shelf modular software framework that facilitates the integration of the different analysis codes. In some instances, multilevel processes are used, rather than "all-at-once" systems for several applications since it seems inefficient to bring every disciplinary design variable and constraint up to the global level. This is commonly the case in structural optimization with detailed structural element models, where both local and global constraints are employed and where local variables are optimized. (See Bennett *et al*[5], Rohl *et al*[10] for examples). One of the advantages of decomposed procedures is that they can be used for multi site operations (Hoenlinger *et al* [9]).

Wakayama and Kroo[4] and Tarzanin *et al* [6] pointed out, however, that currently some of the more successful approaches use close-coupled, all-at-once procedures, however, their success depends, in part, on the fact that automated, fast-running analysis codes (intermediate fidelity level) are used.

As indicated by Rohl *et al*[10], and also Hoenlinger *et al* [9], industry seems to feel that the more sophisticated MDO decomposition processes (e.g., CO, CSSO) are not yet fully proven or sufficiently matured. Rohl *et al*[10] indicate that, in some cases these approaches are not even suited for some of the applications to which they were applied. In other cases, as indicated by Bennett *et al*[5], it may be that the more complicated approaches are not easy to understand or follow and thus simpler processes are selected. Additionally, it seems obvious from the various inputs that decomposition process flexibility is an absolute requirement and that the optimization process must be reconfigurable and tailorable to the specific problem encountered and to possible variations that might emerge in the problem formulation.

Optimization Procedures and Issues

The contributed papers state few requirements on the component optimization capabilities, although Bartholomew[8] points to the lack of robustness of off-the-shelf optimization software. In general, industry practitioners need more experience in the art and science of applying optimization algorithms and interpreting their results. The typical engineering optimization problem is non-linear and non-convex, therefore, a great amount of experience is needed to reliably operate the optimization algorithms. Help in coping with lack of smoothness or scaling requirements, in overcoming slow convergence and local minima problems could significantly reduce the turnaround of typical optimization exercises. Wakayama and Kroo [4] point at the need for more robust and efficient industrial-strength, commercial-grade software to solve large scale problems.

Hybrid schemes that can handle discrete and continuous design variables can prove also be very helpful in an industrial environment according to Bartholomew[8]. Also, Rohl *et al* [10] point out that interdigitation, a procedure by which a combination of different algorithms is used to get to the global optimum of the problem. Tarzanin *et al* [6]encountered local minima and suggested various process to avoid them including a hybrid evolutionary process with NPSOL.

Breadth and Depth Requirements

As detailed by Wakayama and Kroo[4], industrial design processes must possess sufficient breadth. Specifically all of the critical constraints must be considered, otherwise the design will not be practical or feasible. This implies, among other things, that multiple flight conditions must be verified, whether for demonstrating performance, flying qualities or for verifying stress/stability constraints. It has also been pointed out that all of the critical physical mechanisms should be included, to take advantage of all the available design opportunities.

Some authors contend that the highest fidelity models are needed throughout the optimization process, others indicate that various level of accuracy are adequate. The MDO process itself can be used to help determine the fidelity levels required by performing accuracy sensitivity studies on the various critical physical mechanisms in the various disciplines.

Effective Inclusion of High Fidelity Analyses/Test

Bartholomew[8] has a defined set of analysis fidelity levels as follows:

- Level 1: empirical equations,
- Level 2: intermediate level models (e.g., beam theory, panel aero, etc.)
- Level 3: state-of-the-art, high fidelity models(e.g., CFD, FEA)

and has observed that industry MDO is moving toward Level 3 since disciplinary experts usually insist on using the latest, best, and highest fidelity information. If they cannot then they do not feel comfortable with the results. (They may even be uncomfortable with the best analyses /tests results since they are never fully assured that the real world is being faithfully simulated.)

Therefore, effective inclusion of high fidelity data into the design optimization process is necessary, especially for designs at the preliminary and detailed design levels. This may be the most formidable challenge facing industry MDO users and methods developers. Such high fidelity processes are usually neither automated nor robust and many times require hours (even days) of computer time. Allowing an optimizer the opportunity to call such routines as often as it needs to, even if these routines were fully automated, is impractical, so various approximation methods need to be incorporated (Wakayama and Kroo[4], and Tarzanin et. al. [6]).

Approximation and Correction Processes

One class of approximations methods include generic local approximations like Taylor series or variations as well as generic global approximations like response surfaces and neural nets, etc. These provide smooth, simple, explicit analytical expressions that can be generated automatically and that can be called by the optimizer as many times as needed without undue computational burden. Alternately, these approximations can be created concurrently off-line by disciplinary experts who can be responsible for their validity. The challenge in producing these approximations is the trade-off between the amount of data needed to create them, and the control of their accuracy in the design variable space. For approximations in this class, the number of design variables that are strongly coupled still remains small, otherwise, the curse of dimensionality sets in and the approximations become unduly expensive. Also, it is critical to augment them locally to increase their fidelity in certain critical design regions.

Another approximation class uses Level 1 or 2 fidelity disciplinary codes that have been corrected using high fidelity codes, or experimental results (see, for example Chang *et al*, [14], Baker *et al*[15], [16]). In essence, the lower fidelity codes can be used as a “smart” interpolator/extrapolator. The challenge, as underlined by Wakayama and Kroo[4], is to make sure that all of the critical physical mechanisms are represented to some degree/level so that the high fidelity code information can be effectively utilized.

A third class of approximations that can be considered for use in MDO are “Reduced Order” methods[17]. These processes extract the essence of the high fidelity numerical results and expresses them in a relative simple analytic form.

Parametric Geometric Modeling

Bennett *et al*[5] and Honlinger *et al*[9], Radovcich and Layton[7] highlight the need for a shareable common vehicle description to facilitate communication among disciplines and among various companies and sites. Radovcich and Layton[7] report that a single high-fidelity model was used for most of the detail structural sizing and design of the F22 and that this model paid for itself many times over in communication and facilitated analysis and design iteration. They also pointed out that sometimes small changes in structural FEM grids can cause significant changes in internal loads and design, thus it is important to have a high-fidelity model.

Automation is one of the essential requirements for MDO and many authors make the point that parametric and feature-based models facilitate automatic model changes (See, for example Hoenlinger *et al* [9], Wakayama and Kroo[4], Love[12]). Morphing (rubberizing) is one approach at parameterization, but it does not always produce a manufacturable, or even reasonable structural layout. Hoenlinger *et al*[9] indicates, that, in such cases more sophisticated processes are called for which may require fitting continuous processes to discrete layouts.

The resulting unified and parameterized geometry descriptions must be compatible with existing CAD software, however, as indicated by Rohl *et al* [10] additional development work is required since the parametric features of CAD available now are not robust enough for topology optimization. The work on the Technical Data

Modeller and Browser (TDMB) reported by Bartholomew[8] appears to be a response to this need.

Analysis and Sensitivity Capability

Several examples of this were encountered in the contributed papers where middle-level fidelity analysis codes are directly interfaced with the optimizers. (See for example Wakayama and Kroo[4]). This was only possible because of the relatively low computational cost of the individual simulations.

Some papers made use of off-the-shelf single-discipline high-fidelity optimization codes that were either automated (see Tarzanin *et al* [6]) or partially automated (Hoelinger *et al*[9], Bartholomew[8]). In each instance, the detailed analysis is interfaced with the optimizer through approximations of different kinds. Several systems such as STARS, LAGRANGE, NASTRAN Sol. 200, and others are available to automate and facilitate structural sizing but much additional work is yet to be done to fully integrate local panel design (as-built weight, composite manufacturability, cost, and mass balancing). Automated, robust, and efficient CFD analysis, optimization design is also needed but is still in the future.

Industry prefers, in general, to utilize off-the-shelf (OTS) detailed analysis capability when ever possible. Rohl *et al* [10] give a good example of such an application to the design of jet engines which is based on UG, PRO-E, I-DEAS, PATRAN, ANSYS, ABAQUS, NASTRAN, and DEFORM.

It must be emphasized that the drive towards inclusion of all the disciplines relevant to a complete design problem statement still requires major developments in different disciplines. While these developments are mostly outside of the field of MDO itself they deserve reference here.

Satisfactory structural optimization requires detailed aerodynamic loads. A large number of critical flight conditions occur in the transonic regime or at high-angle of attack. While this information is now derived from wind tunnel experiments, significant reduction in design cycle can be achieved by deriving it computationally. Young *et al*[13] detailed the need for a comprehensive aerodynamic database, and, together with Hoenlinger *et al*[9] highlight the need for a methodology for nonlinear aerodynamic loads calculation and identification of critical load cases.

The next step in disciplinary integration for MDO is to bring controls into a full aeroservoelastic formulation of the design problem. Methods are required that enable deriving controls metric and constraints early in the design process, at a time when very little is known of the aircraft configuration (see, for example Hoenlinger *et al*[9], Radovcich and Layton[7], Love[12]).

Finally, central to a successful application of MDO are detailed first-principle-based cost models that include development, manufacturing, acquisition, operations and disposal. (See Love[12], for example.) Other Analysis capability needed are:

- nonlinear aerodynamic loads (Hoenlinger *et al* [9])
- wing load alleviation and aeroservoelastic integ. into str. sizing opt. (Ref.[7, 12]).
- intermed. level fidelity codes (which incl. critical physical mechanisms) (Ref. [4])
- robust reduced order processes

MDO Frameworks & Architecture

Commercial off-the-shelf (OTS) software for MDO frameworks are desired by industry and some are available (iSIGHT, SYSOPT, others) (Rohl *et al* [10], Honlinger *et al*[9]). Some have been tried but the degree of success is uncertain. In addition commercial distributed computing does not seem to be robust (Bartholomew[8]). Industry wants demonstrated, validated MDO software (Honlinger *et al* [9]) that is easy to use.

Databases, Data Flow & Standards

Industry considers database capability to be very important (Young *et al*[13]). It is a repository for current (and past) design data (and the ground rules for generating them) and as such should facilitate communication and reduce cycle time for interdisciplinary data exchange (Bennett *et al* [5]). Such a database must be industrial strength (able to handle huge amounts of data rapidly and should be able to sustain multi site, heterogeneous operation and be user friendly (Radovcich and Layton[7]). A standard set of formats and ground rules for the data (STEP = Standard for The Exchange of Product data) (Bartholomew[8]) will also greatly increase the speed of communication, reduce errors and greatly reduce cycle time. European experience includes projects supported by a "Software Infrastructure Group" and development (Task 8) of database and related tools as follows;

- software version management
- data definition
- database technology
- process definition
- process execution on distributed networks
- data visualization

Computing Requirements

In the case of the F-22 the size of the structural FEM and resulting database was determined by the computer memory (10 terabites) (Radovcich and Layton[7]) required to house the database. CFD analysis and design also poses challenges to computing power. For instance it takes on the order of 10 hours for analysis and about 10-20 hours per design variable for aerodynamic design using the C-90 supercomputer. Thus, if 20 d.v. are used for a design problem then the design would take approximately

300 computer hours. NASTRAN Solution 200 can easily run several days on a high end work station. Distributed computing is probably a necessity for the future to garner enough computing power to perform some of the required analysis functions and to drive multi site operations.

Design Space Visualization
Configuration designers can sometimes be more interested in the design space than the optimum design point. How flat or narrow is the design space near the optimum? How much is lost if an adjacent point is chosen because the optimum point is undesirable? Is the design space precipitous and overly sensitive to errors/noise in the disciplinary modules? How did the optimizer reach the optimum design point? The end result is that it is important to the designer to have user friendly processes for displaying the design space and interpreting the results of the optimization (Tarzanin and Young[6], Honlinger *et al*[9]).

Organizational Structure
Industry is organized along disciplinary lines where each technology group is responsible for maintaining technical excellence, and ensuring that the data generated in that discipline is correct. It is absolutely necessary that this disciplinary control be maintained in any MDO process that is developed. One of these disciplines or technologies is contained in the Advanced/Conceptual Design group. This group is responsible for configuration design and global integration methods and applications. Usually, very approximate analysis methods are used there and so high-fidelity coordination with the various disciplines is minimal. However, for future MDO design such is not the case. If the Advanced/Conceptual Design group is to assume responsibility for MDO at the global level then it will have to change tactics somewhat and provide an integrating function (instead of providing their own simple disciplinary analyses) while allowing the various disciplines to maintain control of the local level design/sub-optimization and data recovery (such as internal FEM loads). In the papers sampled it is the perception that currently no one is in charge of MDO and that an improved company organization would benefit the use of MDO (Honlinger *et al*[9]). Ensuring buy-in of the disciplinary experts to the MDO system may be difficult however (Bennett *et al*[5]).

MDO Operation within IPD Teams
The IPD Team is an essential element in industrial design (References [4, 11, 10, 13]). When MDO is used in the design the IPD team is not replaced but interacts with the process to learn about the design, assess the ground rules, add/replace constraints, furnish guidance in areas not modeled and generally keep the optimization on track (Wakayama and Kroo[4]). An example of this was the composite wing design of Reference 19. MDO is a tool of the IPD Team which is used to assist in selecting and implementing the final design.

Acceptance, Validation, Cost, & Benefits
A lack of understanding of MDO and what it means organizationally is an obstacle to industrial acceptance both by managers and by disciplinary experts (H). Also, Industry can have difficulty in determining both the benefits and development/deployment costs of MDO (Honlinger *et al*[9]). How does a manager assess if there is a net benefit for developing and using an MDO process? Lack of validated results and quantified benefits in the practical industrial environment (not just mathematical process validation) is a big obstacle to its acceptance (References[4, 9]). Specifically, the cost/benefit over conventional design processes is needed. An example of a test that proved that there were benefits of an optimized design is given by (Tarzanin and Young[6]), however, a comparison of the predicted versus actual benefits was not given.

Training
Only recently have universities offered MDO oriented training and so, for the most part, only those in industry that are newly trained are intimately familiar with the formalisms associated with optimization. The rest of the engineering force are, to one degree or other, are having difficulty (Bennett *et al*[5]). This lack of familiarity is an obstacle to the use of MDO in industry.

4. Development Needs for Future Industry MDO

MDO Needs by Category
MDO development needs in industry, as inferred/interpreted from the 10 papers and the experience of the current authors, are presented here. For consistency these needs are categorized in the same fashion as the salient points of Section 3, i.e., the categories shown in the MDO Taxonomy given in Figure 3-2 are used.

*Design Problem Objectives **(Needs)***
Each industrial problem is different and so the biggest need is to have MDO frameworks that are flexible enough to accept whatever objective function is needed. As far as objective function formulation is concerned, research has been, and is being done to provide ways to formulate multiple, difficult or nebulous objective functions. Pareto Front techniques help define the biggest bang-for-buck so that, for instance, the DoD can decide on how much performance it can afford. Also, advances in simplified cost related objective functions have been made (Giesing and Wakayama *et al*[18], Bartholomew[8]) and this type of work should continue.

*Design Problem Decomposition and Organization **(Needs)***

Most high fidelity process (e.g., CFD, FEM) are currently not automated, robust, nor fast enough to be directly called by an optimizer. Thus, a very big challenge is to somehow end up with a design that reflects this high fidelity but does not call it directly by the optimizer. Approximation approaches to this problem are mentioned in that particular category (discussed below). However, in this section the question is; are there decomposition approaches that could accomplish this task? For instance, can approaches be developed that converge to a high fidelity result that only require periodic high fidelity updates to the design process? Currently, analysis methods accommodate and are tailored/adapted to the needs of the optimizer (smoothness automation, etc.), however, this needs to be reversed. Development work on decomposition processes that accommodate and are tailored to the needs/deficiencies of the analysis methods (noise, lack of automation, very large computing time, etc.) are needed since analysis methods are the critical limiting factors in industrial MDO processes.

Optimization Procedure and Issue ***(Needs)***

Improvements in optimization techniques are continuously being made and this must continue since industrial strength, robust, and efficient modules are needed. Industrial strength implies that large problems can be handled (thousands of design variables and constraints). Robust techniques are needed that converge under a wide variety of conditions. Efficient modules are needed to keep the computing time to a reasonable level. User friendly optimization techniques that are insensitive to noise or are "self smoothing" and that provide their own scaling (self scaling) are also needed. Finally robust processes and procedures for escaping local minima and finding the global optimum are needed.

Breadth and Depth Requirement ***(Needs)***

All critical physical mechanisms and critical constraints must be accounted for in an accurate manner for realistic design. *Breadth* indicates the number of disciplines involved (mechanisms and constraints) and *depth* the accuracy/fidelity. Identification of all critical constraints requires experience in the design of the particular vehicle or artifact involved. Identification of the critical mechanisms is more subtle and difficult and requires understanding of the underlying physics of the various disciplines. Experience with high fidelity codes (e.g., CFD) does not necessarily mean that the various mechanisms are understood. Techniques that use the MDO process itself to determine which are the critical constraints and mechanisms would be very helpful.

Effective Inclusion of High Fidelity Ana./Test ***(Needs)***

Two approaches for including high fidelity analyses in MDO have already been discussed, (using a decomposition approach and by using an approximation and correction approach). This section discusses what should be done to the high fidelity methods themselves for direct use in MDO. Currently, many high fidelity processes (such as Navier Stokes, FEM global-local structural sizing) can not be used directly in MDO because they are not automated, robust, nor fast enough to be included. This presents formidable challenges in most disciplinary areas and advancements of the state-of-the-art are required. As each high fidelity technology area matures it becomes more robust and efficient and more subject to automation. Even after maturity however, computing requirements will still be a problem for high fidelity methods.

Approximations and Corrections ***(Needs)***

This may be the single most important need for industrial MDO. As mentioned above many analysis codes (high fidelity or otherwise) can not be put directly into the MDO process and thus approximations and corrections must be used. Response surfaces, neural networks, Taylor series and Taguchi techniques are in current use but robust, efficient, and user-friendly software packages are needed. Procedures that use high fidelity analysis or test data to correct lower fidelity methods are also currently under development but improved techniques are needed in all disciplines. Simple mathematical (non physical) techniques of fudging low fidelity analysis methods need to be upgraded to those that isolate and correct each separate physical mechanism separately. Wakayama's (Reference 4) use of calibrated simple 3-D source flow terms to simulate transonic 3-D effects is an example. Baker *et al* [15,16] have also develoed advanced correction procedures for steady and unsteady aerodynamics and loads. An even more sophisticated approximation procedure is produced using reduced order or parameter identification methods and models (Ref. Baker[17]). Simple examples are state space representations of dynamic aeroelastic models and associated rational function approximations for the unsteady aerodynamics. Other more sophisticated procedures require development, refinement, and extension. Finally, intermediate level fidelity methods can, themselves, be considered an approximation method whose approximating equations are based on physical mechanisms. If all of the critical physical mechanisms are present and a process, including high fidelity adjustments/corrections to each one, are in place then the intermediate fidelity level methods might be thought of as a physics-based interpolation/extrapolation medium for high fidelity codes. This is highly desirable since physics and not mathematics forms the basis of the approximation equations and not just mathematical fitting functions. Figure 4-1 presents examples of the approximation and correction procedures outlined here.

Parametric Geometric Modeling ***(Needs)***

MDO processes require parametric models and automated modeling techniques. Tool kits such as the one being generated under DARPA sponsorship (PMTK) (Reference[10]) will be helpful. Parametric models need to

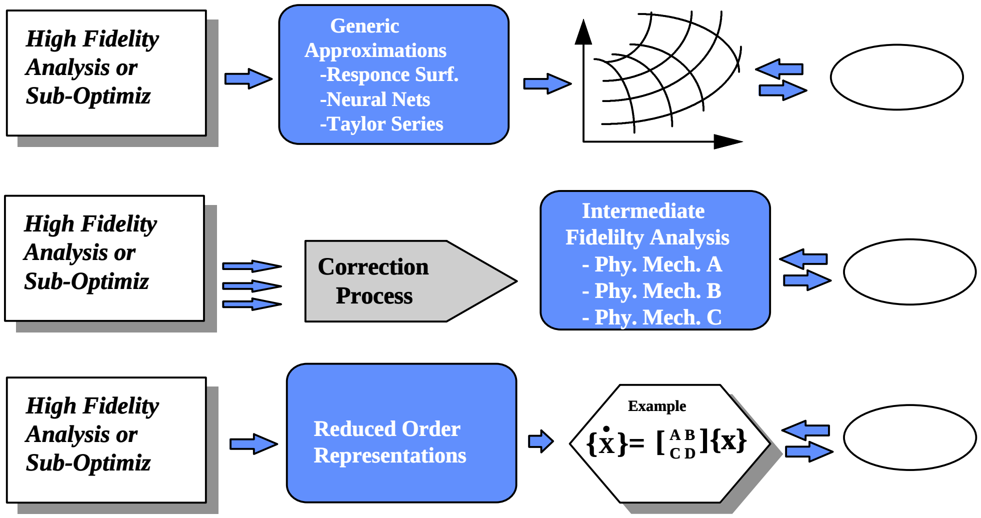

Figure: 4-1 Three Approximation and/or Correction Processes

maintain accuracy and realism as design variables are changed. Thus, for instance, morphing techniques may not be adequate for structural layouts since best industrial practices usually require changing the topology as design variables are changed. Also, straight structural members that become curved during morphing will probably not be acceptable. Robust, automated, and accurate non-parametric models are also required in industry as are interdisciplinary grid/mesh mapping techniques. Well proven software modules for these are needed.

Analysis and Sensitivity Capability ***(Needs)***

Automation is one of the biggest needs with respect to disciplinary analysis methods. An automated analysis will allow the possibility of direct integration into an MDO process and will facilitate the generation and updating of approximations (response surfaces, etc.). Another challenge is the quantification of manufacturing and maintenance cost and constraint requirements into usable models. Cost is usually based on weight even though part count and complexity are much more important for cost than weight. The development and quantification of such models is a definite need in industry. Robust, efficient nonlinear loads analysis methods are also needed as well as well developed aeroservoelastic techniques. A current industry trend is to use well proven, over the counter (OTC) analysis modules and thus development of these is needed in all disciplines. Sensitivity analysis methods did not seem to be high on the list of required technologies, however, such methods are desirable to increase efficiency both for direct inclusion into optimization process or indirectly through the generation of response surfaces and other approximations. Robust CFD (Navier-Stokes) codes both rigid and aeroelastic are needed. Also, an efficient robust global-local structural sizing process is needed that accounts for all of the major structural effects; stress, buckling, aeroelastic loads, local panel design, durability and damage tolerance, flutter, and reversal.

MDO Frameworks and Architecture ***(Needs)***

A mature, efficient, flexible, robust, industrial strength commercial MDO framework is desired by industry. Preferably, a loosely coupled reconfigurable system that can use legacy and other commercial software is best. The architecture should be flexible enough to accept a wide variety of MDO problems.

Databases, Data Flow & Standards ***(Needs)***

Data standards for format, access, and monitoring are needed to facilitate analysis module integration and data transfer. An industrial strength, efficient, and easy to use commercial database system for multi-site, multi-platform operation is also needed. Possibly an Internet based system could be the system of the future if and when it is able to handle large engineering data sets in an efficient manner.

Computing Requirement ***(Needs)***

Current CFD and FEM sizing (e.g., NASTRAN Solution 200) require hours and even days of computer time on high end work stations. This is a formidable barrier to their use in optimization processes. Improving computing power with the use of massively parallelized machines will improve this situation especially if analysis codes can be re-programmed to take advantage of them. Specifically, new subroutines and algorithms (e.g. matrix operations, eiganvalue analysis etc.) designed to take advantage of multiple processors are needed. In this case a straightforward process of re-programming existing analysis codes would be desirable. In this regard the HPCCP (High Performance Computing and Communication Program is dedicated to demonstrating "teraflops computing" since it is assumed that this is the wave of the future. If clusters of work stations are used instead then efficient and robust distributed computing controller systems are needed. If the controller can span multiple sites then this will potentially open up a large resource for computing. This system, however, must be very versatile since work stations are usually available only on an intermittent basis and scheduling and coordinating would be a very challenging task.

Design Space Visualization ***(Needs)***

Commercial MDO frameworks must provide easy to use optimization and design space visualization/interpreting since designers are sometimes more interested in the space around an optimum than the optimum itself. The largest challenge in this regard are techniques for visualizing a multidimensional design space. Since it is impossible to visualize anything beyond three-dimensions creative ways of interpreting or depicting the design space need to be invented. These depictions could require a lot more computing operations than the optimization process itself.

Organizational Structure ***(Needs)***

Industry itself needs to adjust their organizations to facilitate MDO. Disciplinary groups would still develop and maintain technical excellence and be responsible for the accuracy and integrity of design data in an autonomous fashion. The responsibility for interfacing and coordinating all of the disciplines into an MDO process will have to be assigned to an MDO group. All of the disciplines will work together with the MDO Group as a team to decide on the interface processes. It makes sense that the MDO Group also is responsible for global configuration optimization and this job is currently being done by the Advanced Design Group. Does it then make sense to broaden the role of the Advanced Design Group to assume the responsibility of the MDO function?

MDO Operation in IPD Teams ***(Needs)***

Industry itself needs to address this issue since IPD Teams are now a permanent part of the industrial landscape and are an ideal place to direct the MDO efforts. The MDO Group (or Advanced Design Group) may conduct the configuration optimum operations and perform trade studies that may not fit the optimization process, however, the IPD Team will direct this effort at a higher level. The IPD Team must get used to using MDO as a tool that they can direct. Design philosophy, ground rules for design, critical constraint selection and definition, restraints on the design, trade studies, etc. will all be directed by the disciplinary, tooling, manufacturing, maintenance, and cost experts that comprise the ITD Team.

Acceptance, Validation, Cost & Benefits ***(Needs)***

The major need in this category is to produce a series of full industrial validation cases. These validations must be practical industrial strength cases and preferably done on actual vehicles. A firm validation based on test is preferred where the additional benefits of MDO, over and above current design practices, are quantified and compared to the additional effort/cost of MDO.

Training ***(Needs)***

Industry is not used to the formalisms and use of optimization and MDO and thus training materials and courses that are meaningful to industry are needed. Also, new university graduates that are already properly trained are also needed.

Satisfying MDO Development Needs

The needs outlined in this section impact every sector of the MDO technology development community including universities, government labs, commercial software companies, and industry itself. Universities and government labs can help advance the state-of-the-art for disciplinary and MDO technology. Industry, can efficiently transfer this technology into practical use in industrial design. Commercial software companies can provide off-the-shelf industrial strength capability to set-up and execute major multi-site design problems. The resources required for this development are very large and will have to come from multiple sources with maximum leveraging. A team approach is needed that coordinates plans and resources to ensure long range success. Figure 4-1 presents an illustration of this cooperative thrust.

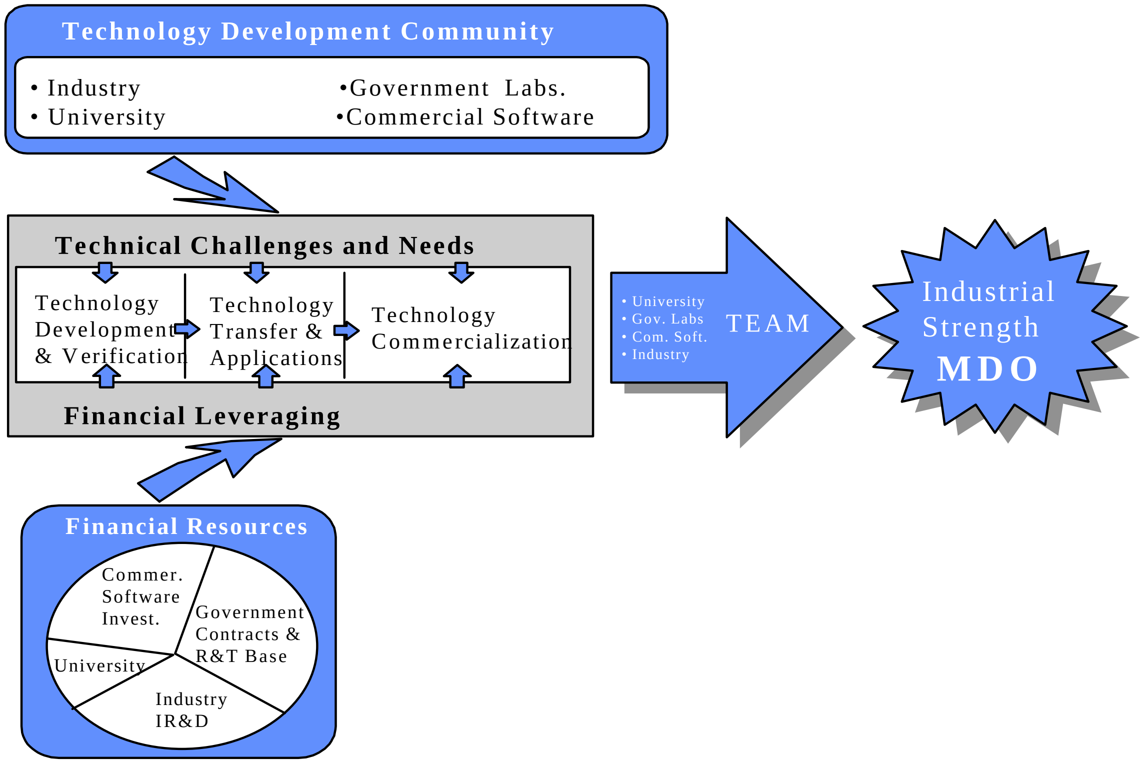

Figure 4-2: Teaming of MDO and Disciplinary Technology Development Community

5. Conclusions

A series of 10 invited design papers has been reviewed with the purpose of providing the MDO technology development community with a distilled view of industry applications, challenges, and needs. A wide variety of industries (airframe, automobile, rotorcraft, jet engine, space), and design problems (feasible design, trade studies, structural sizing, sub-optimization, dynamic response minimization, and full configuration MDO) were contained in the papers reviewed. The process of summarizing the papers and presenting the final results was as follows. First, a brief synopsis of each paper was presented to give an overview of the *applications* reviewed. Second, the *challenges* and salient points from each paper were delineated into one-line sentences which were then sorted into logical categories for various elements of MDO (Appendix I). These logical categories were based on an extension/revision of an existing taxonomy (classification of MDO elements) by Sobieski[3]. Thirs, a general summary of each category was then written which was based on the salient points contained in that category. Finally, a summary of the MDO development *needs* for industry was given after distilling them from all of the categorized data. Even though the sample of papers was limited it is felt that a very good representation and cross-section of industrial applications, challenges and needs has been given and that the conclusions of the data contained here will be helpful to the MDO technology development community for prioritizing future MDO development. The technology development needs are wide ranging and will require the cooperative involvement of universities, government labs., industry, and commercial software developers to answer these needs.

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[6]Tarzanin, F., and Young, D.K., "Boeing Rotorcraft Experience with Rotor Design and Optimization," AIAA

Paper 98-4733, presented at the 7th AIAA/ USAF/NASA/ISSMO Symposium on Multidisciplinary Analysis and Optimization, St. Louis, MO, Sep 98.
[7]Radovcich, N., and Layton, D., "The F-22 Structural Aeroelastic Design Process with MDO Examples," AIAA Paper 98-4732, presented at the 7th AIAA/ USAF/NASA/ISSMO Symposium on Multidisciplinary Analysis and Optimization, St. Louis, MO, Sep 98.
[8]Bartholomew, P. "The Role of MDO within Aerospace Design and Progress Towards an MDO Capability Through European Collaboration," AIAA Paper 98-4705, presented at the 7th AIAA/USAF/NASA/ISSMO Symposium on Multidisciplinary Analysis and Optimization, St. Louis, MO, Sep 98.
[9]Hoenlinger, H., Krammer, J., and Stettner, M., "MDO Technology Needs in Aeroservoelastic Structural Design," AIAA Paper 98-4731, presented at the 7th AIAA/ USAF/NASA/ISSMO Symposium on Multidisciplinary Analysis and Optimization, St. Louis, MO, Sep 98.
[10]Rohl, P., He, B., and Finnigan, P., "A Collaborative Optimization Environment for Turbine Engine Development," AIAA Paper 98-4734, presented at the 7th AIAA/USAF/NASA/ISSMO Symposium on Multidisciplinary Analysis and Optimization, St. Louis, MO, Sep 98.
[11]Lillie, C., Wehner, M., and Fitzgerald, T, R., "Multidiscipline Design as applied to Space," AIAA Paper 98-4703, presented at the 7th AIAA/USAF/ NASA/ISSMO Symposium on Multidisciplinary Analysis and Optimization, St. Louis, MO, Sep 98.
[12]Love, M. H., "Multidisciplinary Design Practices from the F-16 Agile Falcon," AIAA Paper 98-4704, presented at the 7th AIAA/USAF/NASA/ISSMO Symposium on Multidisciplinary Analysis and Optimization, St. Louis, MO, Sep 98.
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[14]Chang, K.J., Haftka, R.T., Giles, G.L., and Kao, P.J., "Sensitivity-based scaling for approximating structural response," Vol. 30, pp. 283-287, 1993.
[15]Baker, M. L., Yuan, K., Goggin, P. J., "Calculation of Corrections to Linear Aerodynamic Methods for Static and Dynamic Analysis and Design," AIAA Paper 98-2072, presented at the 39th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, Long Beach, CA, April 1998.
[16]Baker, M. L., "CFD Based Corrections for Linear Aerodynamic Methods," presented at the 85th Meeting of the AGARD Structures and Materials Panel, Aalborg, Denmark, 14-15 Oct. 1997 and contained in AGARD Report 822, entitled, "Numerical Unsteady Aerodynamic and Aeroelastic Simulation," March 1998, pg. 8.
[17]Baker, M. L., Mingori, D. L., Goggin, P. J., "Approximate Subspace Iteration for Constructing Internally Balanced Reduced Order Models of Unsteady Aerodynamic Systems," AIAA Paper 96-1441, presented at the 37th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, Salt Lake City UT, April 15-17, 1996.
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Appendix I: ***Salient Points from the 11 Papers Sorted by Catagories***

<u>Legend</u>
Y=Young, Anderson, & Yurkovich
W=Wakayama & Kroo
L=Love
H=Honlinger, Krammer, & Stettner
R=Rhol, Beichang, & Finnigan
B=Bennett, Fenyes, Haering, & Neal
Bw=Bartholomew
Rl=Radovcich/Layton
T=Tarzanin & Young
Lwf=Lillie/Wehner/Fitzgerald

<u>Design Formulations & Solutions</u>

- Design Objectives
  - Minimize TOGW. *W*
  - Large aeroelastic structural sizing/optimization of aircraft. *H*
  - MDO math. formulation and definition of "Best" is a problem. *W Y L*
  - Accuracy of Obj. Funct. may be off by 100%. *Y*
  - Objective function hard to formulate. *Y L*
  - Most important is satisfying constraints. *Y Lwf*
  - Second most important is Robustness. *Y*
  - Better design, Nearest local opt. mostly continuous design variables. *H*
  - Feasible, better design, mostly continuous, large no. of d.v. and constr. and multiple obj. *H*
  - Reduced cycle time, discover critical aspects early, model manufacturing; continuous process definition from definition to product. *H*
  - Reduced weight, maintain performance, detailed design. *Rl*

- DOC (Direct Operating Cost) heuristically approximated with very simple linear combination of weight and drags at various flight conditions. *Bw*
- Frontier Project uses Pareto Front techniques to identify "biggest bang for buck." *Bw*

• Design Problem Decomposition and Organization
  - Definition of MDO excludes flight simulation. *Bw*
  - BWB is a highly coupled problem and used an all-at-once MDO formulation i.e., included all d.v. (mission, aero, str., etc) at the global level. *W*
  - Industry processes are sequential; MDO requires concurrent processes. *H*
  - MDO technology not yet mature enough for industrial use. *H*
  - MDO strategies for multisite operation is needed. *H*
  - How do you use CO to include high fidelity results. *W*
  - Just use trade study and DOE approach. *L Y*
  - Just add more analyses to trade study approach (MDO not needed). *L Y*
  - Advanced decomposition processes are OK if they prove themselves. *Y*
  - Needed when high fidelity involved. *W*
  - Interdigitized optimization could prove useful. *R*
  - CO and CSSO may not be very practical. *R*
  - How do you make CO practical. *W*
  - Need a distributed optimization process. *R*
  - Going to loosely coupled processes for MDO since source code not available for OTS MDO codes like iSIGHT. *R*
  - Global/Local process needed; Sub optimization of disciplines used. *B*
  - Complex large scale optimizer not needed; used ADS. *B*
  - Must go toward loose coupling to make further progress in MDO. *B*
  - Suitable MDO method is needed. *H*
  - CSSO CO class of decomposition too complex and little understood. *H*
  - CSSO CO class of decomposition immature for Industry. *H*
  - CSSO CO class of decomposition lacks software. *H*
  - Loosely coupled process needed to handle all of the constraints. *Y*
  - Tightly coupled needed to be efficient and enable to perform in reasonable time. *W*
  - Had to use tightly coupled system to make practical. *T*
  - Loosely coupled preferred. *H*
  - Tightly coupled needed for special problems. *H*
  - Both are needed. *H*
  - Design done in cycles requiring sequential steps. Various disciplines lagged several cycles; loads/ flutter; one cycle, fatigue; 2 cycles, elastic-to-rigid effects on maneuver flight simulator; three cycles. Some disciplines performed several cycles for each global cycle. *Rl*
  - Sometimes had to get "forward looking" models to help leap frog the global iteration. *Rl*
  - Challenge is to provide tools to integrate disciplines. *Bw*
  - Europe moving toward loosely coupled systems. *Bw*
  - Conceptual Design is multidisciplinary but low fidelity. *Bw*
  - Preliminary Design is fragmented and configuration flexibility lost. *Bw*
  - Don't need close coupled black box. *Bw*
  - Do need loose coupled modular framework that can use legacy codes. *Bw*
  - Multilevel Global-Local Structural optimization employed in GARTEUR. *Bw*
  - MDO process needs to be flexible and reconfigurable. *Bw*
  - Industrial design process does not necessarily fit a particular MD procedure. Need flexibility and reconfigurability. *B*

• Optimization Procedures and Issues
  - MDO problem Size is an issue. *W*
  - Smoothness can be a problem. *W R*
  - Local minimums is a challenge. *T*
  - Ways to get around local minimums. *T*
    1) New starting point.
    2) Broaden move and constraint limits initially.
    3) Change wt. factors in Obj. Function.
    4) Update fixed parameters periodically.
  - Increase robustness by incrementally tightening constraints as optim. progresses.
  - Structural sizing optimization. *Rl*
  - Manual "optimization" facilitated by common high fidelity FEM, rapid turn- around on cycle updates, performing strength/fatigue sizing first then iterating for flutter. *Rl*
  - Direct use of optimizer less attractive due to the number of possible function calls to high fidelity analysis routines; possibly use a hybrid scheme. *Bw*
  - Design variable linking needed. *B*
  - MDO robustness is lacking since different sites end up with different optimums. *Bw*
  - Optimize system by running simulation of interdisciplinary process. *Lwf*

<u>Analysis Capabilities & Approximations</u>

• Breadth vs Depth Requirements
  - All critical constraints needed otherwise weird results (e.g. pointed wing tips). *W*
  - All critical mechanisms needed otherwise may loose a mechanism to optimize. *W*
  - Must have high fidelity or results are useless. *Y*
  - Inability to analytically (instead of wind tunnel tests) determine design variable sensitivities is a need. *Y*

- Need capability for multiple configurations, fuel, stores, actuator failure. *H*

• Approximation and Correction Processes
- Response Surfaces may be too big and expensive. *W*
- Response Surfaces play a key role. *L*
- Use RS, Neural Nets, Taylor Series. *B*
- Lack of Intermediate Fidelity Codes is a problem. *W*
- Approximation based processes. *H*
- Use Approximation models. *B W*
- Approximation generation software needed. *H*
- Correct intermediate methods using high fidelity data *(References 15 and 16)*
- Used nonlinear wind tunnel test data to correct linear loads (especially with reference to control surfaces). *Rl*
- Use Response Surfaces to reduce cost. *B W*

• Effective Inclusion of High Fidelity Analyses/Test Results in Optimization and Design
- Close coupled process made high fidelity possible. *T*
- Replacing Wind Tunnel data in design process. *Y*
- Possibly use Response Surfaces. *W*
- Used an automatic FEM generator. *H*
- Rapid CFD for air loads. *Y*
- Need high fidelity propulsion integration for BWB; cannot effectively include it at intermediate fidelity level. *W*
- Fidelity levels categorized; *Bw*
  Level 1- empirical modes (e.g. conceptual design)
  Level 2- intermediate level (e.g. beam str. models, panel aero etc.)
  Level 3- State-of-art high fidelity (e.g. CFE, FEM)
- MDO is moving toward Level 3 fidelity. *Bw*
- Analysis times for high fidelity codes can make MDO problem intractable. *R*

• Parametric Modeling
- Need parametric geometric mode compatible with current CAD systems. *R*
- Parametric CAD not robust enough for topology optimization. *R*
- Need parametric/associative modeling and speed up analysis. *L*
- Automated robust model generation needed. *H W*
- Lack of layout/material distribution algorithms. *H*
- Discipline models too complex. *H*
- Standard product process models and interfaces catering to it. *H*
- Automation and ease of use and checking is a barrier in disciplinary analysis integration to MDO. *H*
- Single high fidelity FEM used for stress, loads, flutter, allowables, fatigue, aeroelastic effectiveness. *Rl*
- TDMB (Technical Data Modeller and Browser) can develop a fully parameterized aircraft configuration and associated aero, FEM and AE models. Data conforms to STEP standards. *Bw*
- Unified parameterized geometry description. *B*
- Need shareable common vehicle description and approximations, easy ways to interact back and forth with various disciplines. *B*
- Common models for structural, thermal, and optical needed. *Lwf*

• Analysis and Sensitivity Capability
- Affordability missing in design. *L*
- Move away from weight based cost. *L*
- Manufacturability in design is needed. *L*
- Need missing engine-out constraint for BWB. *W*
- Bring controls into structural design process (early). *H L*
- Need to bring controls further up in the design process. *L*
- Nonlinear loads database is a big barrier. *Y*
- Sensitivities will be used when design community gets use to them. *Y*
- Aero wind tunnel data can not produce sensitivities needed in optimization. *Y*
- Need aeroservoelastic integration. *H*
- Need capability for multiple configurations, fuel, stores, actuator failure. *H*
- Lack of Robustness is a barrier to use of disciplinary analysis in MDO. *H*
- Employed high fidelity fuel tank loads. *Rl*
- Used CFD and test to determine Hammer Shock. *Rl*
- Maneuver load active controls used to reduce weight. *Rl*
- STARS code used for structural optimization. *B*
- LAGRANGE code used for structural optimization. *H*
- Need nonlinear aero but is complex. *H*
- Need standardized tool interfaces and disciplinary analysis tools which are developed with interdisciplinary interfacing in mind. *H*
- Moving to OTS codes for analysis and MDO (UG, PRO-E, I-DEAS, PATRAN, ANSYS, ABAQUS, NASTRAN, DEFORM etc.) *R*
- Applicability to MDO is a barrier to use of disciplinary analysis in MDO. *H*
- Working on a full structural, thermal, optical simulation process. *Lwf*
- Large internal load changes due to FEM grid changes/refinements. *Rl*
- Important margin of safety changes due to small internal load or FEM changes. *Rl*
- Composite tailoring impractical due to costs associated with testing/databases. *Rl*

<u>Information Management, Data Flow & Processing</u>

• MDO Frameworks & Architecture
- Use the iSIGHT generic MDO system. *R*

- Developed GM system tailored to car design. *B*
- Industry wants to use off the shelf tools AD included. *Y*
- Use generic Genie system and GUI but not commercially available system. *W*
- Stopped developing LAGRANGE because it might be better to go to a general architecture. *H*
- Need a flexible user configurable MDO architecture. Current commercial optimization codes over sensitive to details, do not always converge to optimum, and are not very flexible. *Bw*
- Commercial distributed computing not robust. *Bw*
- GSE software is lacking. *H*
- Software integration tools needed for design process organization. *H*
- Demonstrated Validated MDO software is needed. *H*
- Interfacing various systems together and keeping versions of software working is a concern. *Lwf*

• Databases, Data Flow & Standards
  - Common databases, database management all help. *Y*
  - Tool interfaced do not match. *H*
  - Tool interfaces is a barrier. *H*
  - Data standards are needed. *H*
  - Database updating of data and the ground rules that generated them. *B*
  - ORACLE database used. *Rl*
  - Terabyte data handling needed. *Rl*
  - Recent projects supported by "Software Infrastructure Group." *Bw*
  - Need common standards for data definition and intercommunication vehicle (STEP=standard for the exchange of product data). *Bw*
  - Multi-site MDO and data capability needed. *Bw*
  - European MDO Process (Task 8) have provided the following tools; software version management, data definition, database technology, process definition, process execution on distributed networks, data visualization and optimization. *Bw*
  - Common database used for F/A-18 E/F. *Y*
  - Database as support for Response Surfaces. *T*
  - Interdisciplinary data conversion and transmission is a problem. *Lwf*

• Computing Requirements
  - F-22 needed a widely distributed, very heterogeneous computing system. *Rl*
  - Very large memory 10 Terabytes needed for F-22. *Rl*
  - The amount of data stored for the F-22 was so large that the process had constraints on the amount of information manipulated. Plies were optimized later in the process because of that. *Rl*
  - Distributed computing used for F/A -18 E/F. *Y*
  - Computing infrastructure and available deployed hardware not kept up to demands of MDO. *R*

• Design Space Visualization
  - Need graphic visualization. *H*
  - Need process for extracting characteristic features of a family of designs. *H*
  - Interpreting results is an obstacle to optimization. *H*
  - User friendly monitoring tools would be beneficial. *H*
  - Need design space display. *T*

<u>Management & Cultural Implementation</u>

• Organizational Structure
  - No coordinating person for MDO in industry. *H*
  - MDO should be someone's job in industrial organization. *B*
  - Conflicting requirements impedes MDO implementation - Conceptual Design. Dept. says that MDO code does not include all the needed disciplines- Analysis Dept. says that your models are too simple. *B*
  - Industry sometimes lacks math skills and has difficulty with MDO formalisms. *B*
  - Improved company organization would benefit use of MDO. *H*
  - Loss of control by disciplinary experts is an issue. *H*
  - Coordinated Tri-company team by instituting detailed ground rules, guidelines, and policies. *Rl*
  - Cross functional, partners, different locations. *Rl*
  - Coordinating and scheduling of multisite MDO important. *Bw*

• MDO Operation within IPD Teams
  - Integration of IPT and MDO needed. *W*
  - IPT Needed to keep opt. on track. *W*
  - IPT (key organizational element) Needed to help decide on opt. config. Y
  - Common High fidelity FEM model used to facilitate communication and reduce cycle time and errors. *Rl*
  - Non optimal design of long lead time items (actuators). *Rl*
  - Budget profiles did not always match process flow requirements. *Rl*
  - Variations in results due to ground-rules which may not be known ahead of time. *Bw*
  - IPD team direction and learning is needed to help direct MDO and its ground rules. *Bw*

• Acceptance, Validation, Cost & Benefits
  - Validation is a MDO Cultural Acceptance Problem. *W*
  - MDO produces benefits over conventional design in performance, weight and in providing baselines for further analysis. *W*
  - Lack of acceptance of MDO by management and disciplinary experts. *H*
  - Lack of validated MDO results is an obstacle to use of optimization. *H*

- Quantification of MDO benefit versus MDO development cost is missing. *H*
- Imbalance of fidelity is an obstacle to acceptance of discipline trading via MDO. *W*
- Large common FEM (and associated computing bill) paid for itself many times over in reduced cycle time, increased communications and reduced errors. *Rl*
- Future European SM to verify MDO and its benefits. *Bw*
- MDO gives clear benefits as shown by tests (however no comparison with expected improvement). *T*

• Training
- User familiarity and training is an obstacle to using optimization. *H*
- Engineering force having difficulty with optimization formalisms and precisely defining objective function. *B*
- New engineers are more familiar with optimizaiton tools. *B*